PDHonline Course E464 (4 PDH)

Optical Fibers, Lasers and Modulators

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Roy Timpe, P.E.

1. Introduction

Ever look at fiber in a conduit and wonder about what is going on inside that plastic jacket? Ever wonder about how you can get information sent to you from a computer in another continent, and not pay for the computer time, or the long distance transmission? This has been made possible by the great reduction of the cost of data transmission, largely due to fiber optics. The goal is to familiarize the reader with the devices used in these fiber optic systems. Optical fiber, and some of its limitations are discussed. Semi-conductor lasers, detectors, and modulators are introduced. Various advantages and disadvantages of methods of modulating the data are discussed. Laser safety is also introduced as it applies to these fiber optic systems.

2. Waveguide Geometry

Optical fibers are actually dielectric wave guides. Typically they have a cylindrical core surrounded by a cladding. Both the core and cladding are made from glass. However, the glass is designed such that the cladding has a lower index of refraction than the core. This allows there to be total internal reflection of the light traveling down the core of the fiber.

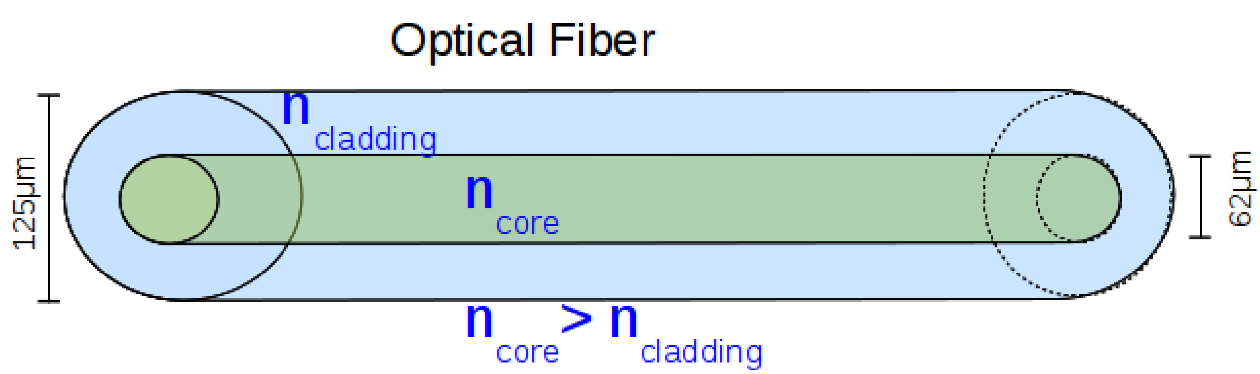


Figure L1.

A multi-mode fiber is depicted above with a core diameter of 62 microns. In actuality, if you solve Maxwell's equations for the fiber above with the 62 µm core, you will find that more than one mode can exist for the wavelength range of 800 to1600 nm. The speed of light in a dielectric is given by the equation:

$$v = c/n$$

where v is the speed of light in the fiber, c is the speed of light in a vacuum, and n is the index of refraction of the fiber core. The several modes that Maxwell's equations predict will have "tails" of intensity that travel in the cladding. These modes will have a different percentage of their energy that actually travel in the cladding, and thus these modes travel down the fiber at slightly different speeds, since they all actually experience a different "effective" index of refraction.

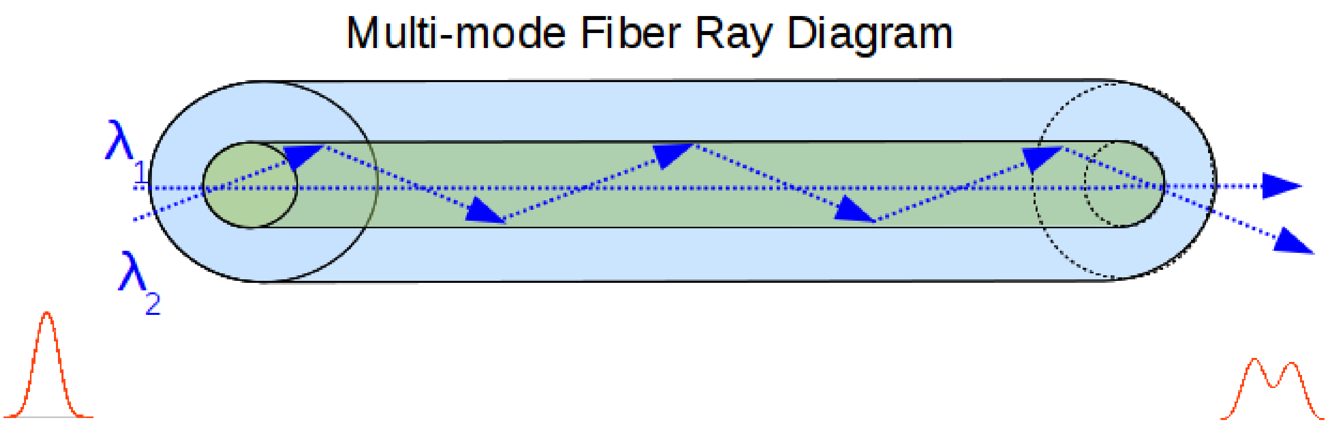


Figure L2

Rather than dealing with Maxwell's equations, it is simpler to look at the multi-mode fiber from a ray optics perspective. The figure above shows two light rays entering a multi-mode fiber, and emerging out the other side. Notice that what enters the fiber as a single light pulse leaves the fiber as a double pulse. This is because the energy making up the pulse traveled to the other end of the fiber in two modes, and the modes arrived at the other end at different times. The light represented by λ_1 traveled directly to the far side of the fiber, while the light represented by λ_2 traveled to the far side after experiencing several internal reflections.

It is undesirable to have the energy in the fiber arrive at the far side at different times. This spreading of the pulse could cause a "ZERO" to be perceived as a "ONE." Maxwell's equations predict that if the core diameter is shrunk down only one mode can exist in the fiber. The core diameter required is 9 μm for the wavelengths we are interested in. The following figure shows a single mode fiber from a ray diagram perspective.

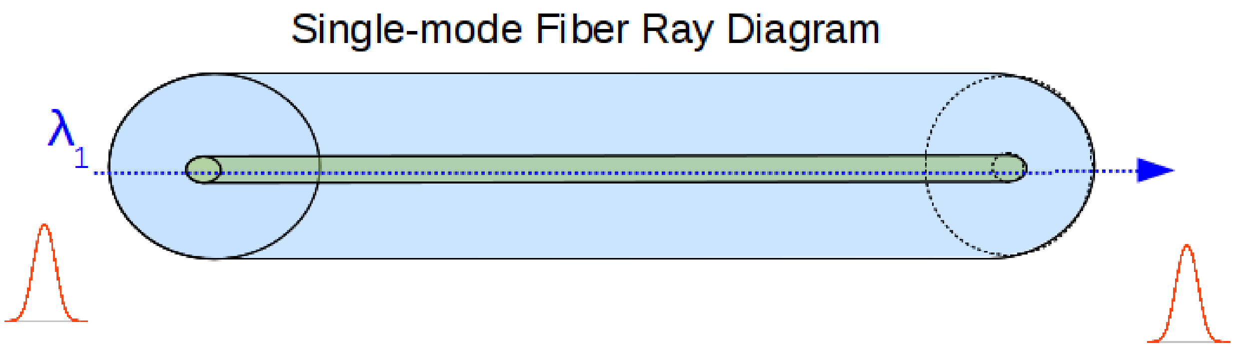
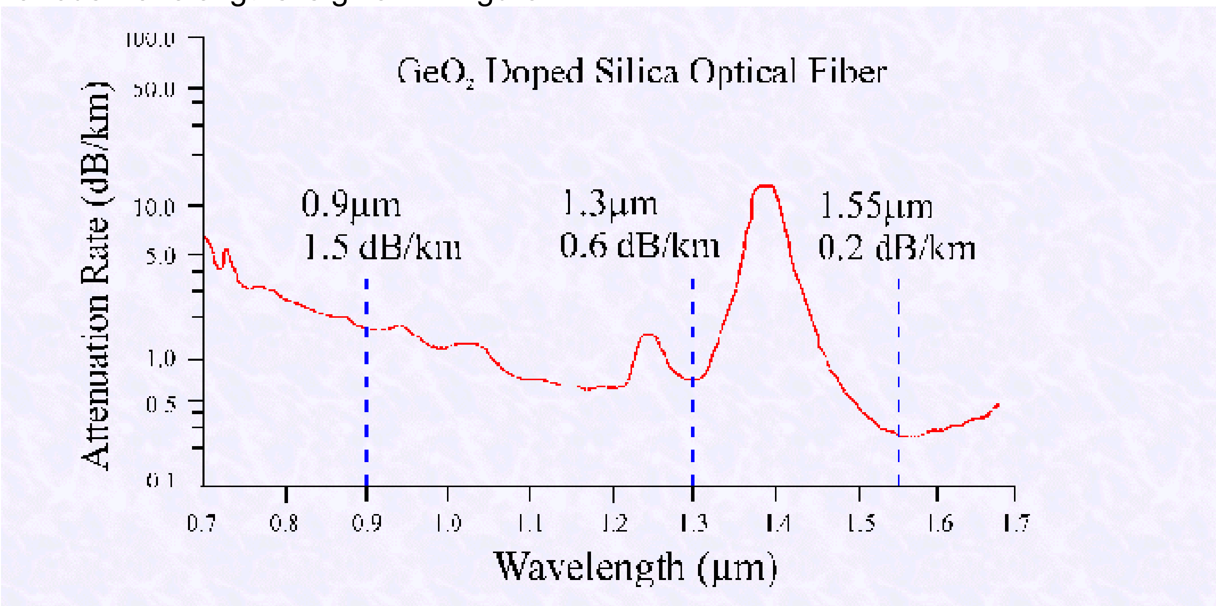


Figure L3

Typical core diameters for multi-mode fiber are 62 µm and 50 µm while single mode is 9 µm . Multi-mode fibers will have an orange PVC jacket, while single mode fibers will have a yellow PVC jacket. This color code nearly always applies to single fibers in a jacket. If there is a fiber bundle or array (for example 8 fibers in a row forming a ribbon like cable) you can not rely on the yellow/orange color code.

Waveguide Materials:

The material of choice for optical fibers is usually silica glass. The attenuation for the various wavelengths is given in Figure L4.



Loss Characteristics of a Silica Optical Fiber
Source: "Study of Indium Tin Oxide (ITO) for Novel Optoelectronic Devices"
Ph.D. thesis by Shabbir A Bashar
http://www.betelco.com/sb/phd/ch2/c25.html

Figure L4

Notice that the lowest loss in the fiber occurs around 1550 nm or 1.5 µm. The 1300 nm (or 1.3 µm) point is also of interest because the fiber has the lowest material dispersion at this wavelength. The 850 nm wavelength was historically one of the first to be used, due to the availability of solid state lasers in that wavelength. It is still a popular wavelength today for multi-mode applications due to the low cost of these lasers.

Long haul single mode systems will usually use multiple wavelengths in the 1550 nm range. The first trans-Atlantic optical fiber (circa 1984) used the 1300 nm wavelength. Later undersea applications would use 1550 nm lasers once they became available, and proved reliable enough for these applications.

3. Dispersion

Dispersion is the tendency of the fiber to spread an optical pulse in time. We already saw that the multi-mode fiber could do this because the different modes propagated at different speeds. There is also material dispersion. The index of refraction is actually a function of wavelength. Remember that ***v= c/n*** the velocity of the light in the fiber is given by the speed of light in a vacuum divided by the index of refraction. Since the index is actually a function of wavelength, we could say:

$$v = c/n(\lambda)$$

Since the index of refraction is actually a function of wavelength, light at 1550.01 nm will travel slightly faster than light at 1550.00 nm. Since the lasers we use do not produce a totally pure tone, the material itself will tend to broaden the pulses as they travel down the fiber. Spreading o the pulse due to ***n(λ)*** is called wavelength dispersion, as opposed to modal dispersion shown in the multi-mode fiber.

4. Diodes

Both the lasers used to transmit data and the detectors used to convert the optical data back to an electrical signal are diodes.

A diode is a check valve for electricity. The symbol contains an arrow showing the direction of positive current flow when the diode is forward biased. The symbol with two circles on the left represents a current source. The symbol on the right with the parallel plates represents a voltage source, like a battery. The ideal current source will change its voltage as required to achieve the desired current set point. Likewise an ideal voltage will change its current as required to maintain the voltage set point. The reverse biased diode will only have a slight leakage current. The diode leakage current is a function of the structure of the diode, the materials used to fabricate the diode, and temperature. Diode leakage currents are often measured in nano amps. A well designed InGaAs PIN detector diode is likely to have a less than 1 nano amp leakage current. Diode leakage current is sometimes also called "dark current" since any light incident on the diode during the measurement will result in an artifact.

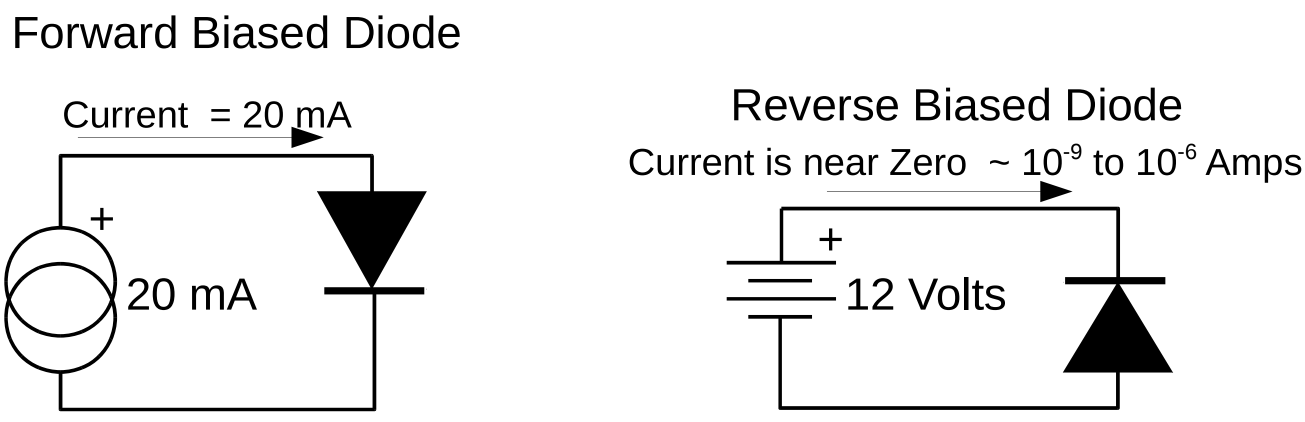


Figure L5

5. Lasers

The term "laser" originated as an acronym for Light Amplification by Stimulated Emission of Radiation. In reality these lasers are oscillators so it could more properly be called Light Oscillation by Stimulated Emission of Radiation, but the DOT-com bubble of the late 1990's would not have been possible if the venture capitalists had been asked to invest in technology founded on the “loser.”

Spontaneous & Stimulated Emission:

Figure L6 shows an energy diagram for a semiconductor.

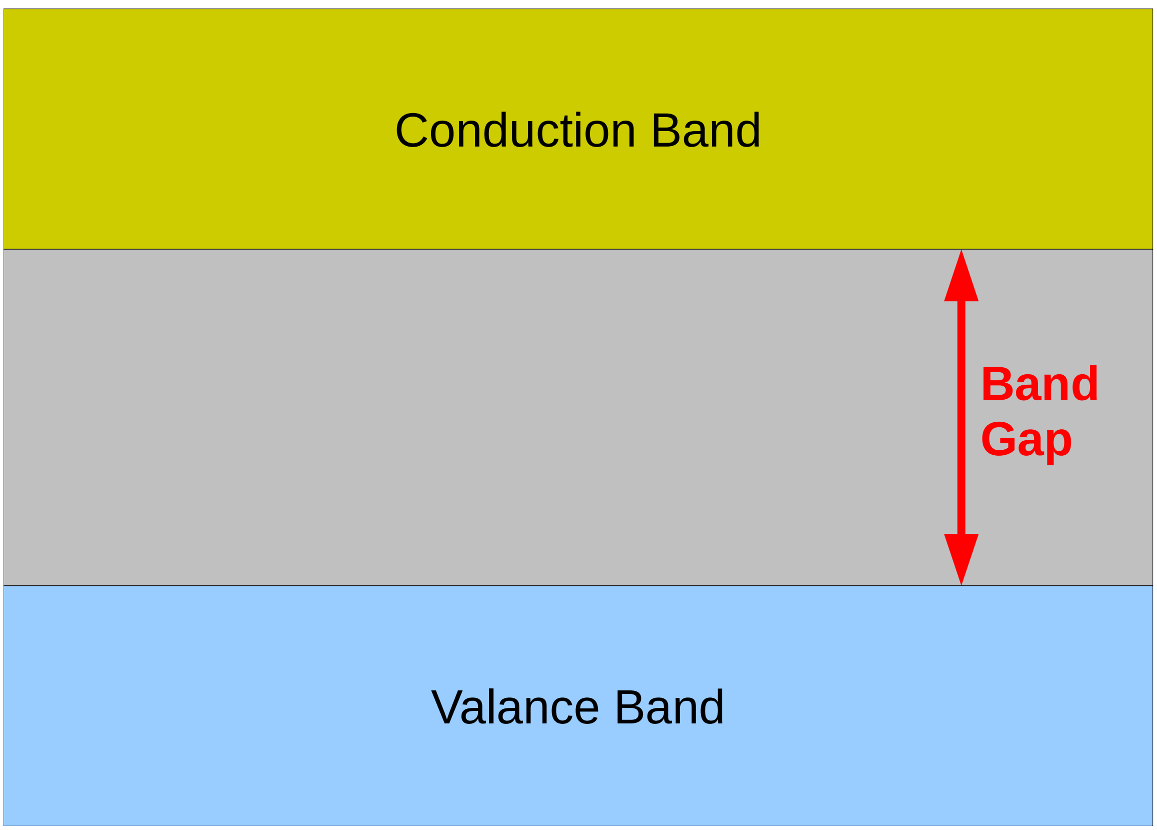


Figure L6

Notice that the electrons can be in the conduction band or the valance bad, but they can not occupy the gap in the middle.

If an electron were to drop from the conduction band to the valance band, there is an energy difference that needs to be appreciated. Depending upon the material this energy could be a phonon (an acoustic wave) in the crystal or it could be a photon.

The materials we are interested in will result in photons being given off when these electrons make this transition.

Figure L7 shows an electron dropping across the band gap and giving off a photon.

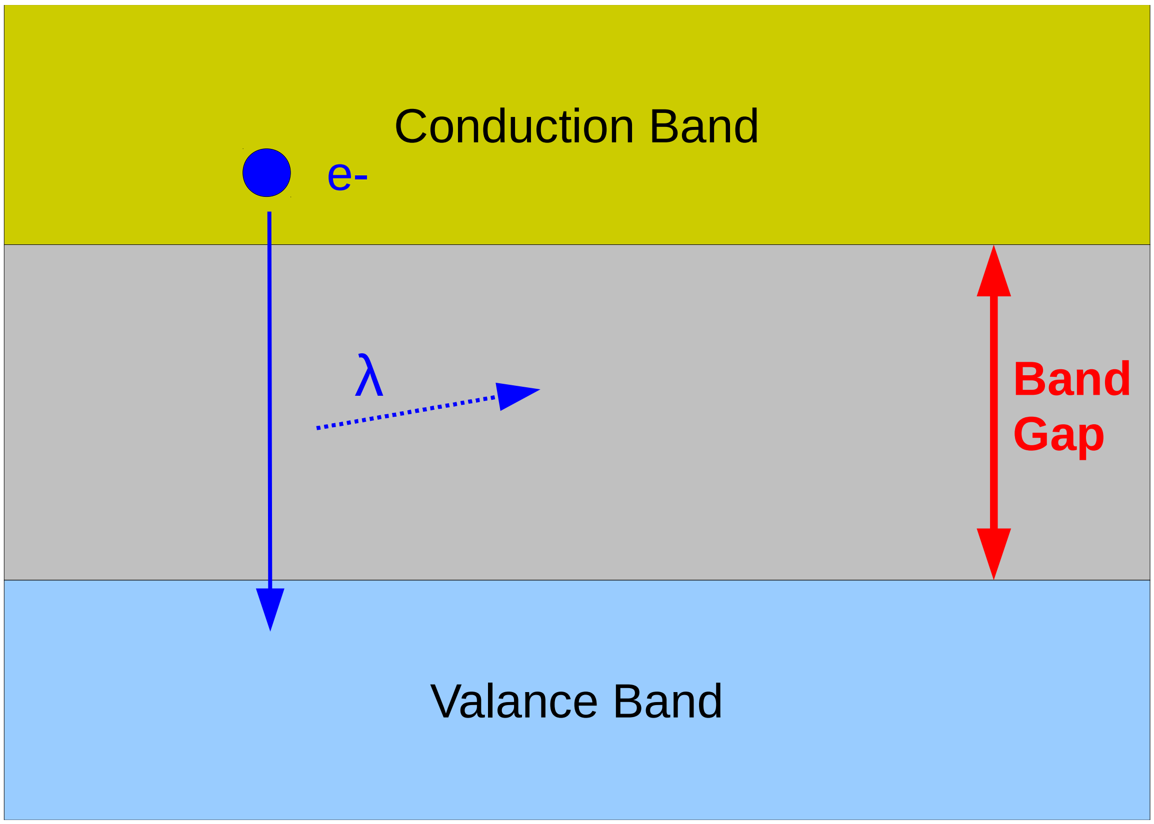


Figure L7

This is called spontaneous emission since the electron just spontaneously makes the jump.

The next figure shows three electrons undergoing spontaneous emission.

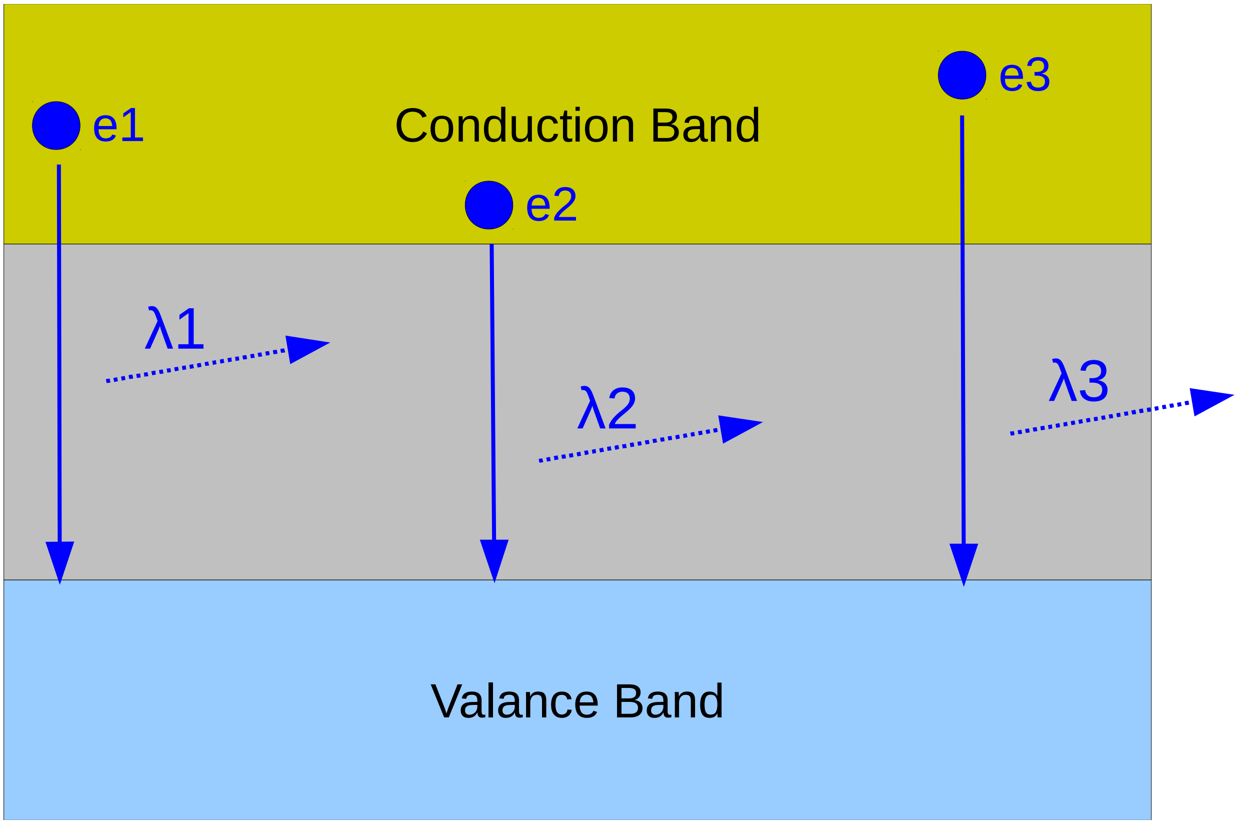


Figure L8

Notice that e3 is giving up more energy than e1. Also, e2 is giving up the least energy. This means that photon λ2 will have the least energy (i.e. the lowest frequency, thus the longest wavelength). In this example we would expect $\lambda 2 > \lambda 1 > \lambda 3$.

Finally, we have stimulated emission.

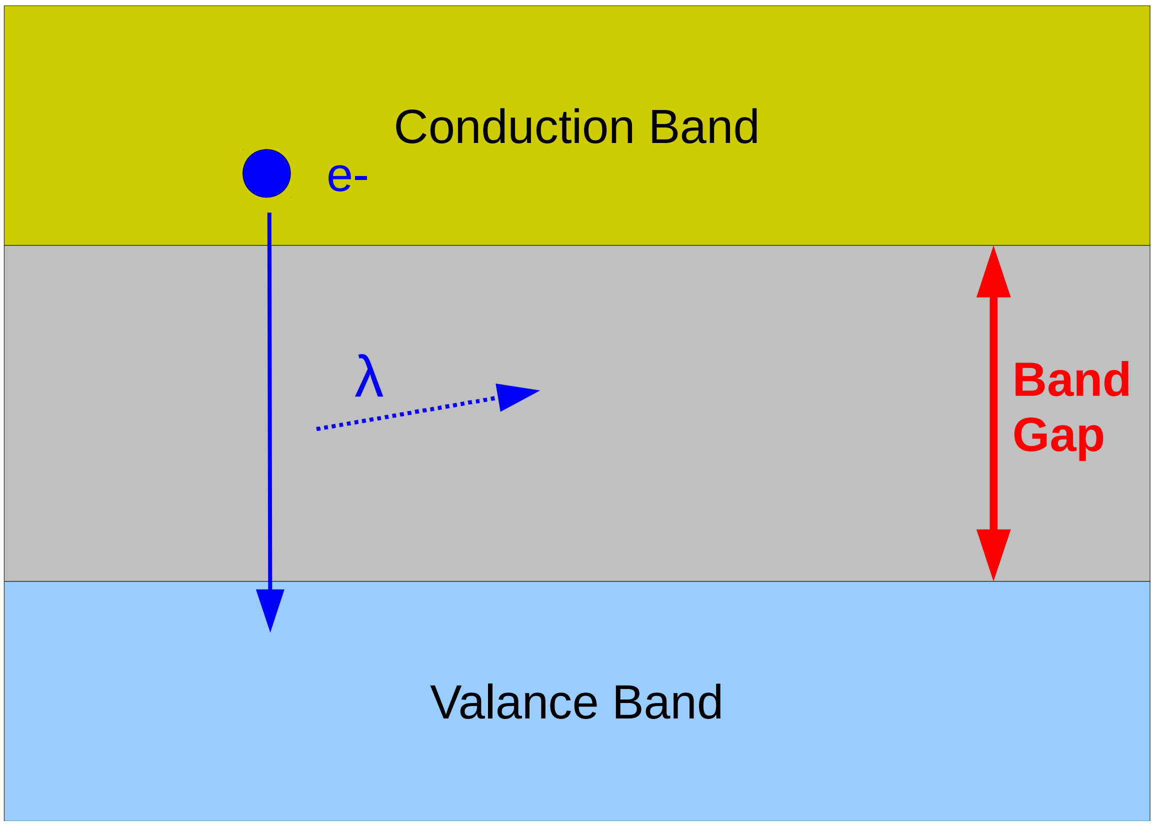


Figure L9

Stimulated emission is when a photon causes an electron to jump. The resulting second photon is the same wavelength and phase of the original photon. (λ2 = λ1) It is stimulated emission that is responsible for the amplification of light in the laser.

Absorption:

We just learned that when electrons go from the conduction band to the valance band a photon is produced. Likewise, the semiconductor material can absorb photons. For lasers absorption is a loss to be overcome. For detectors absorption is used to detect the photons.

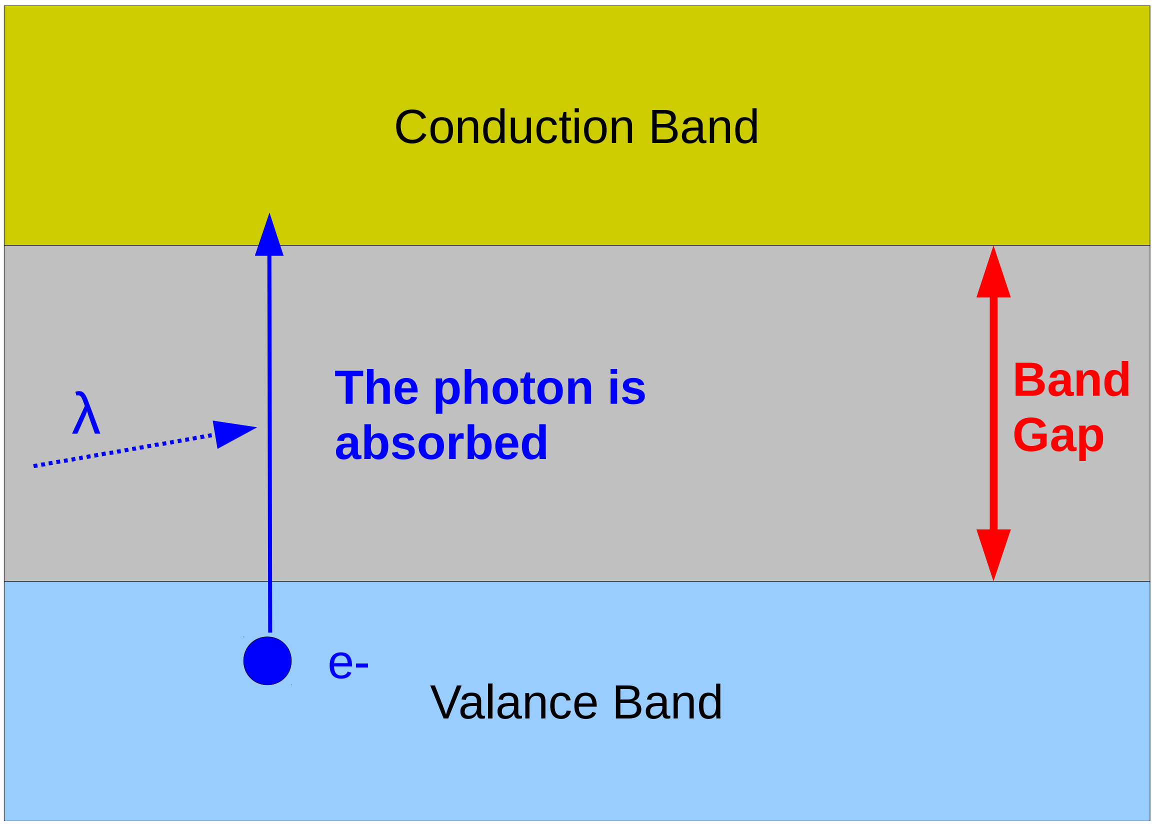


Figure L10

Population Inversion (getting the gain):

In order to get optical gain we need a population inversion. There have to be more carriers in the conduction band than the valance band. If this were not the case, absorption would use up all the photons we make by stimulated emission. More carriers in the conduction band than the valance band is called a population inversion. This is done by applying a forward bias to the semiconductor diode.

Getting the feedback to cause oscillation:

If we place this semiconductor in an optical cavity, we can get the optical feedback necessary to make a laser. The simplest cavity would be two plane mirrors facing each other such that the light is reflected back and forth through the semiconductor. This is a Fabry–Pérot cavity.

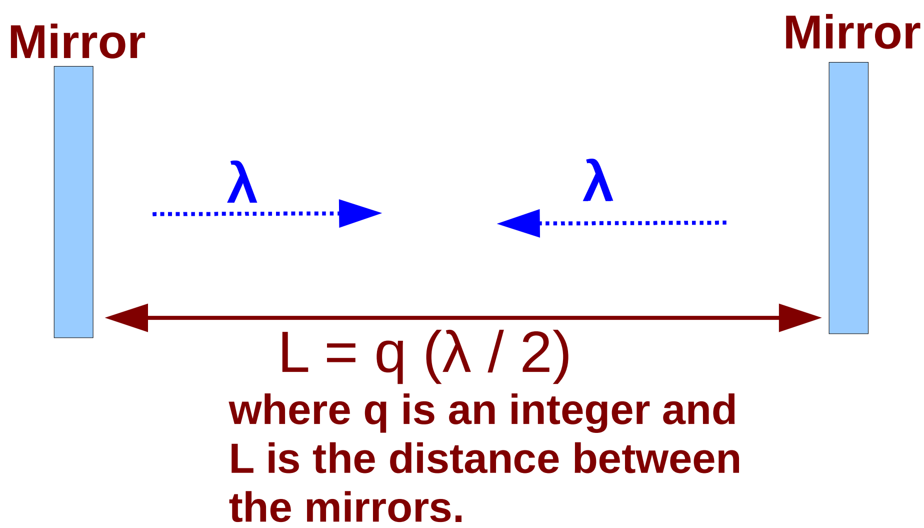


Figure L11

Notice that many modes can exist in the cavity, but the relationship between the modes has to satisfy the equation: $L = q(\lambda / 2)$ where q is an integer.

The semiconductor has gain, due to stimulated emission. This gain operates over a range of wavelengths (or frequencies). A typical gain curve is shown below for a material with gain in the 1300 nm region.

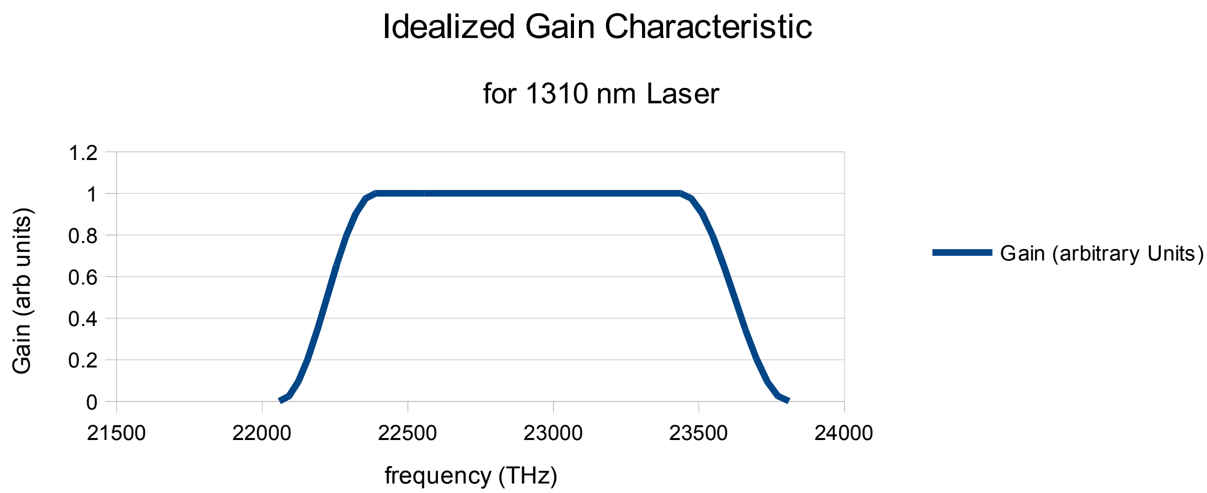


Figure L12

The width of the gain curve is due to the fact that all the electrons in the conduction band do not necessarily have exactly the same energy. Now often several of the cavity modes occur in the range where the material has gain. This is shown below.

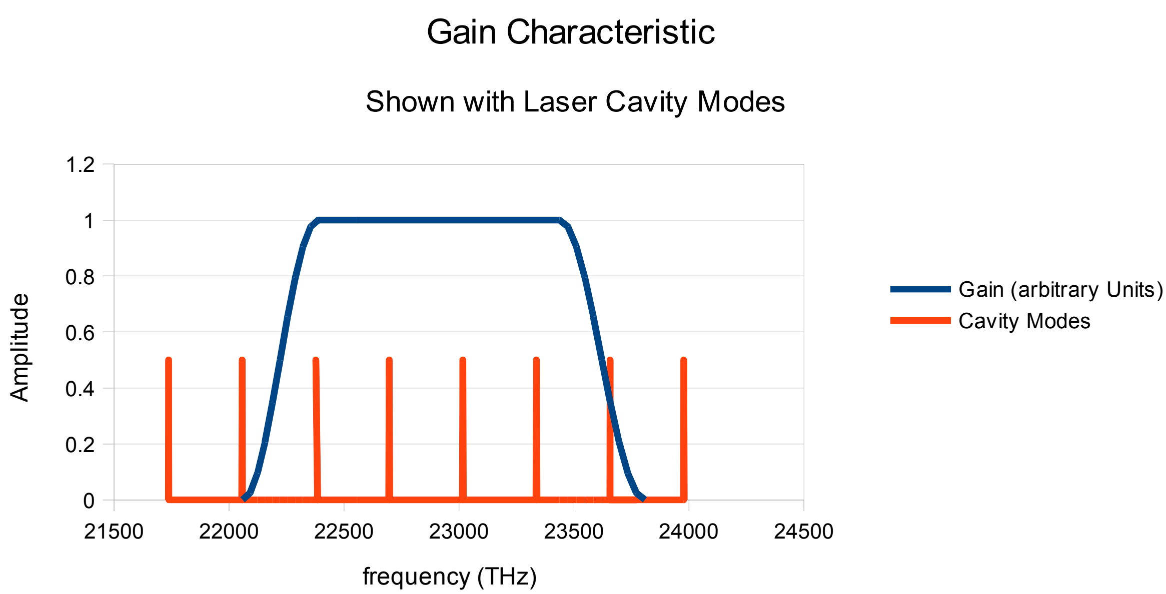


Figure L13

So in this example, the semiconductor has nice gain from 1270nm (23,600 THz) to 1350nm (22,200 THz) There are 4 cavity modes (each with a sequential value of q from L = q λ / 2) that receive sufficient gain from this material. The result is that the gain in the region of the cavity modes is reduced, because the electrons in the conduction band with the energy required to support the four cavity modes are used to support those modes. This reduction in gain at the cavity modes is called "hole burning."

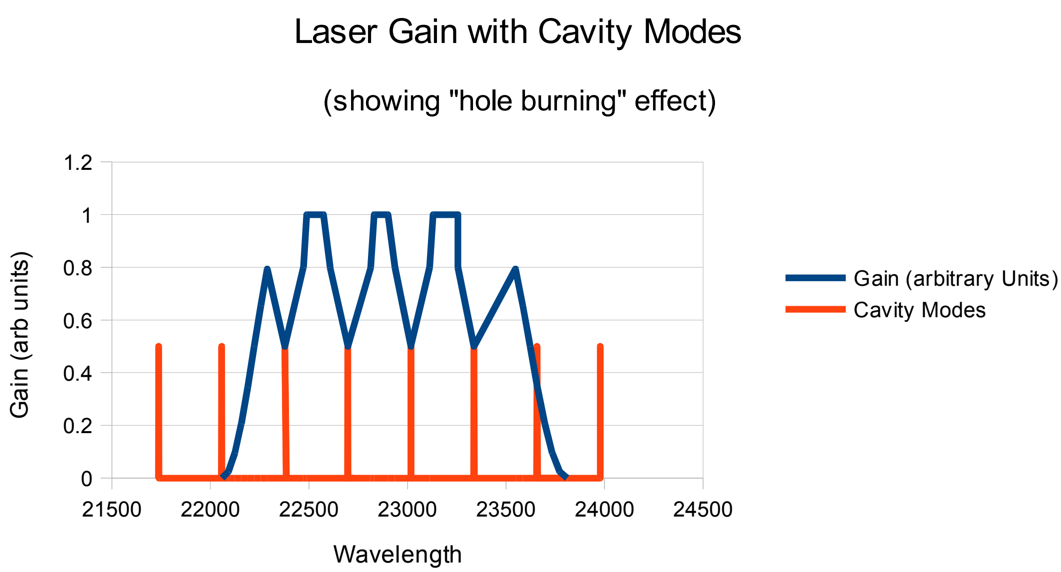


Figure L14

In this example, we have a diode with sufficient forward bias to give the gain curve shown. Some photons are created by spontaneous emission. Those photons of the correct wavelength (i.e. supported by one of the cavity modes) are feed back and amplified by stimulated emission. In practice, the cavity (parallel mirrors) is formed by cleaving the semiconductor crystal. The planes in the crystal lattice are perfect for forming the parallel mirrors required.

The laser diode has light coming out of both the front and the back, since the mirrors are created by the cleaving of the crystal lattice. The ratio of front light to back light can be adjusted using coatings applied to the mirror surfaces, but all semiconductor lasers have some light coming out of the back facet.

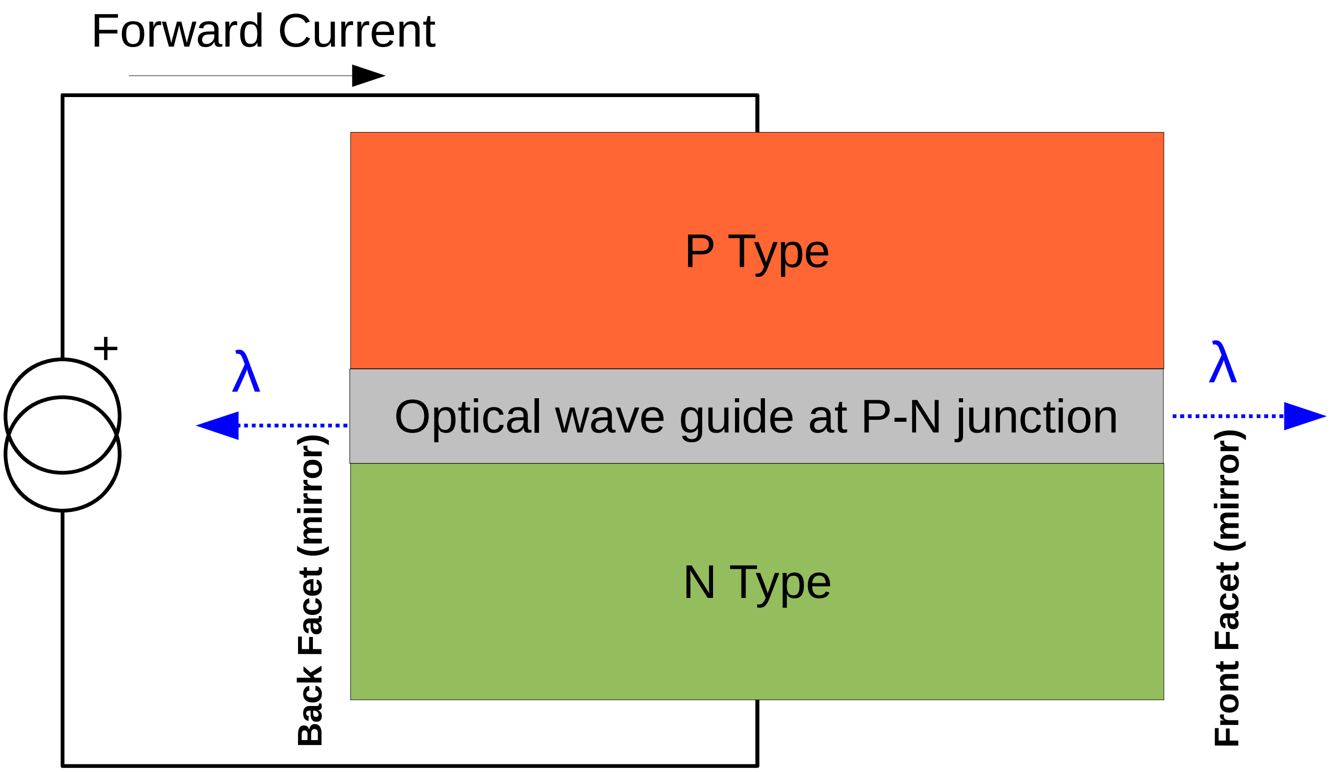


Figure L 15

The Laser Light vs. Current (L- I) Characteristic:

Initially, as the diode is forward biased, the gain is not sufficient to overcome the losses (due mostly to mirror loss, and absorption). The laser diode is like an LED (light emitting diode). The photons are not the same wavelength and phase. Their wavelengths range all over the gain curve of the semiconductor. As the diode current is increased, finally the gain is sufficient to overcome the cavity losses. The light becomes coherent (i.e. it is now nearly all the same wavelength and phase). The slope of the curve dramatically increases. In other words, you get a lot more light out per unit of current increase. The current where this dramatic change occurs is called the threshold current. Threshold current increases with temperature. In the example curve below, the threshold current is 8 mA. The LED region of the curve (current < 8 mA) is linear with a much lower slope than the laser light region (current > 8 mA) of the curve. Typically the laser light region of the curve is concave down. This is due to heating of the laser diode. The step from 80 mA to 81 mA does not yield as much increase in light as the step from 13 mA to 14 mA. The orange dashed line represents the ideal. The concave down portion of the curve is most pronounced when the laser diode is measured CW (continuous wave or with DC current). If we were to measure the same diode Light vs. Current with fast current pulses as say 1% duty cycle, the resulting curve would follow more closely the dashed orange line. In fact, the difference between the CW L-I curve and a pulsed L-I curve can be used to evaluate the quality of the bonding of the laser diode to the heat-sink. The better the bond the less the CW curve will be concave down.

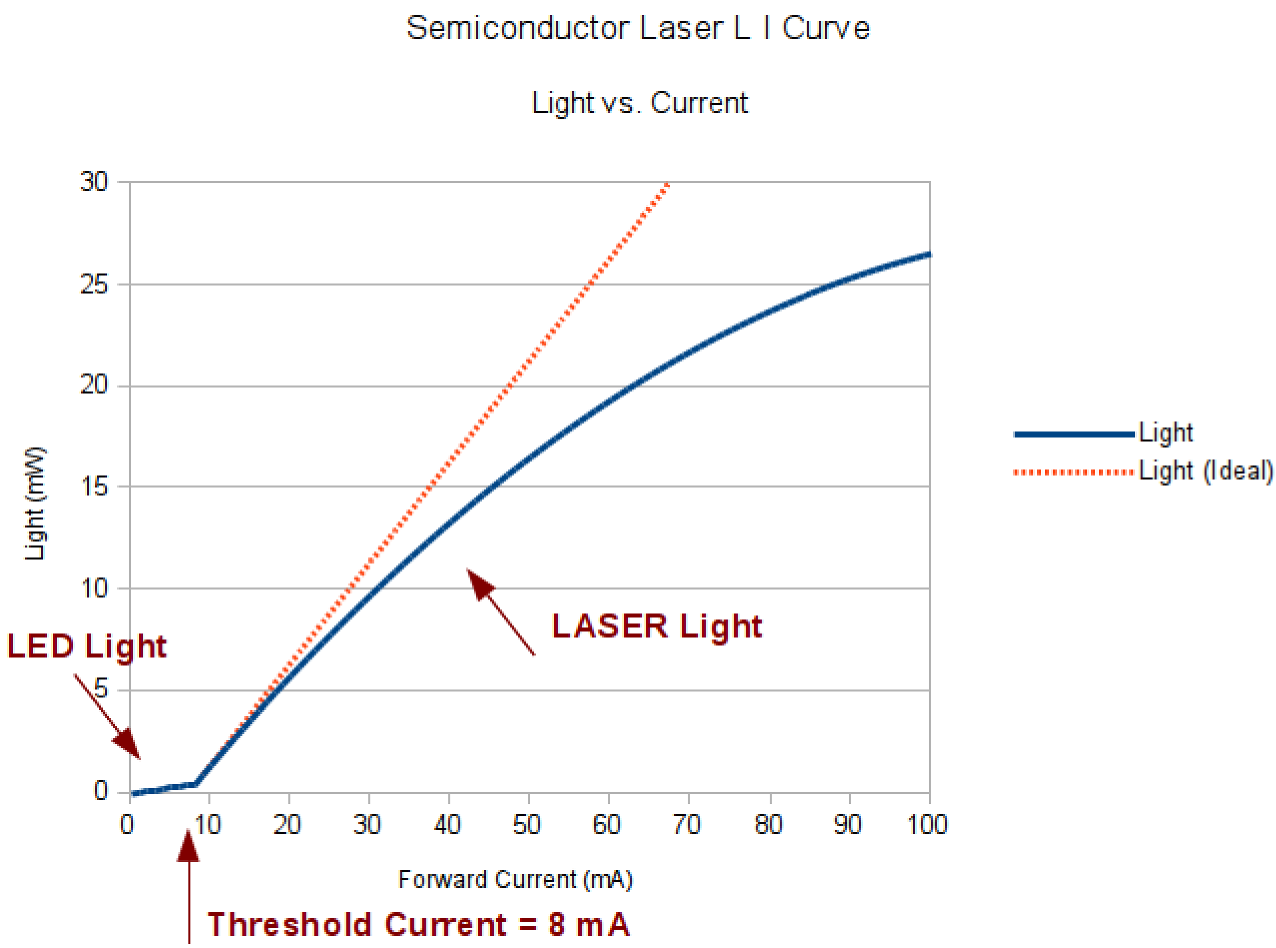


Figure L 16

Single Mode lasers:

All semiconductor lasers will have a L-I curve similar to the one shown above. The laser described above (1300 nm with 4 lasing modes) is multi-mode since there are 4 cavity modes that are supported by the material gain characteristic. Since the index of refraction of the fiber is a function of wavelength, the multi-mode laser would only be desirable for short runs. Long fiber runs would cause the energy from some of the cavity modes to arrive at the receiver at different times. (Remember wavelength dispersion due to $\boldsymbol{v = c/n(\lambda)}$). If the energy from some of these modes were to arrive at what should have been a ZERO, this additional energy could cause the receiver to see the ZERO as a ONE. Multi-mode lasers like this are often used with multi-mode fibers for distances of 100 – 300 meters. Lower bit rates allow longer fiber runs. For long distance runs it is desirable to have a single cavity mode under the gain characteristic. Rather than use just the cleaved crystal lattice to create the mirrors for the cavity, a grating is created inside the active area of the semiconductor such that only one cavity mode is supported by the semiconductor gain curve. This method is called distributed feedback since the feedback occurs throughout the semiconductor and not just at the cleaved crystal lattice edges. These lasers are referred to as DFB lasers. DFB lasers are always single mode.

6. Using the laser to transmit data

There are several ways to transmit data using a laser. One way is direct modulation. The laser itself is toggled between two points on the L-I curve to produce optical ONES and ZEROS. In the next figure, we will zoom in on the region near threshold. Notice that we are switching the current between 9 mA and 16 mA to get the laser to switch between 1 mW output and 4 mW output.

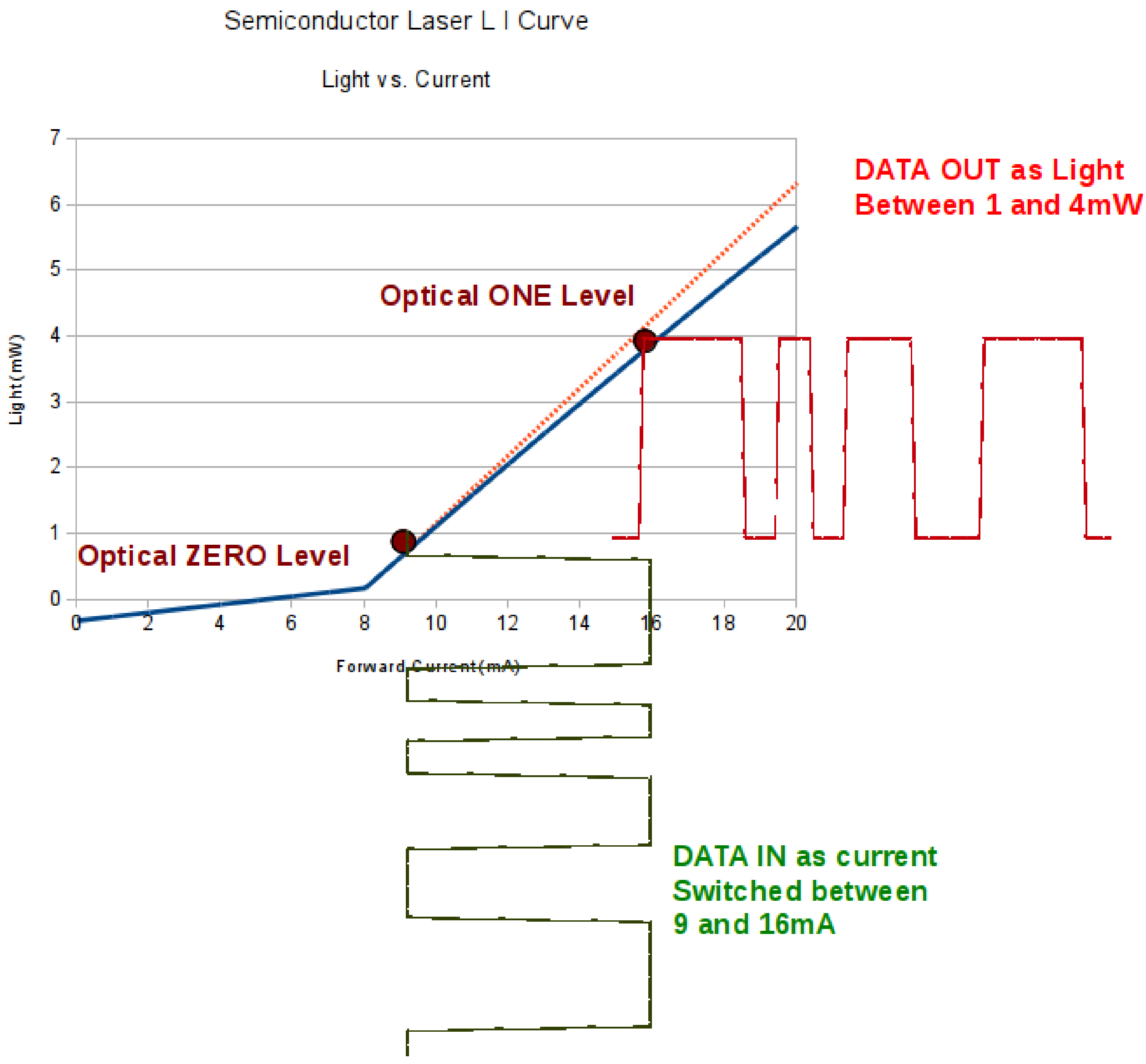


Figure L 17

In this example, the optical ZERO Level is 1 mW and the optical ONE level is 4 mW. There is a parameter called extinction ratio (ER) usually expressed in dB.

Extinction Ratio is calculated as follows:

$$\mathbf{ER = 10 \log (P_1 / P_0)}$$

where P_1 is the power level of the ONE and P_0 is the power level of the ZERO.

In the above example the ER = 10 log (4.0/1.0) = 6.02 dB. A high extinction ratio gives the signal better performance in the presence of noise, however, in the case of a directly modulated laser allowing the optical ZERO level to be below threshold can cause excessive chirp. All oscillators have chirp when they start their oscillation. For example, a guitar string does not instantly play the note it's tuned to when it is first plucked. It rapidly settles into the tuned note. Likewise the laser will produce light that is off the desired wavelength when it is first turned on. This is especially true when the optical zero level is below threshold.

7. Detectors

Once we have the digital data expressed as light pulses in a fiber, all that is left is to detect them at the other end. Detectors are diodes that use absorption to convert the photons into an electrical current. These detectors are diodes and are nearly always reverse biased.

P-N junction Depletion Region:

A P-N junction is formed by doping the intrinsic semiconductor material. The intrinsic material will have an equal number of holes and electrons. If some atoms are introduced with an extra electron in their valence band, that makes the intrinsic material N type. The dopant is a donor of electrons. If atoms are introduced with fewer electrons in the valence band, that makes the material P type. The dopant is an acceptor of electrons. The electrons in the N-type material diffuse across the junction into the P region and likewise the holes from the P region diffuse into the N region. The electrons are leaving their donor atoms in the semiconductor. These atoms are ionized, but are also in the lattice and can not move. The same is true of the atoms trapped in the P-Type lattice. These ions in the lattice create an electric field that opposes further migration of the electrons and holes. This area at the junction is called the depletion region. Reverse biasing the diode increases the width of the depletion region.

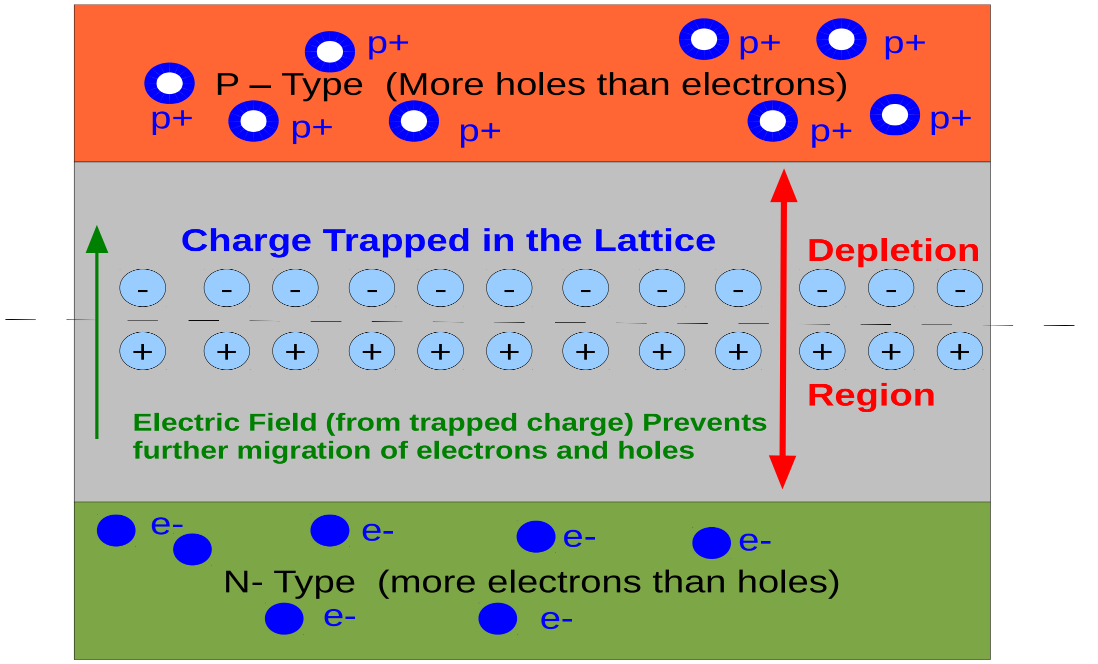


Figure L 18

Photons can be absorbed anywhere in the semiconductor. However, photons that are absorbed in the bulk P region (or N region) will likely not be detected. The resulting electron hole pair is most likely to recombine before being detected. If the photon is absorbed near the P-N junction, the electron and hole will be swept apart by the electric field in the depletion region before they have a chance to recombine. Photons absorbed in or near the depletion region are likely to be detected.

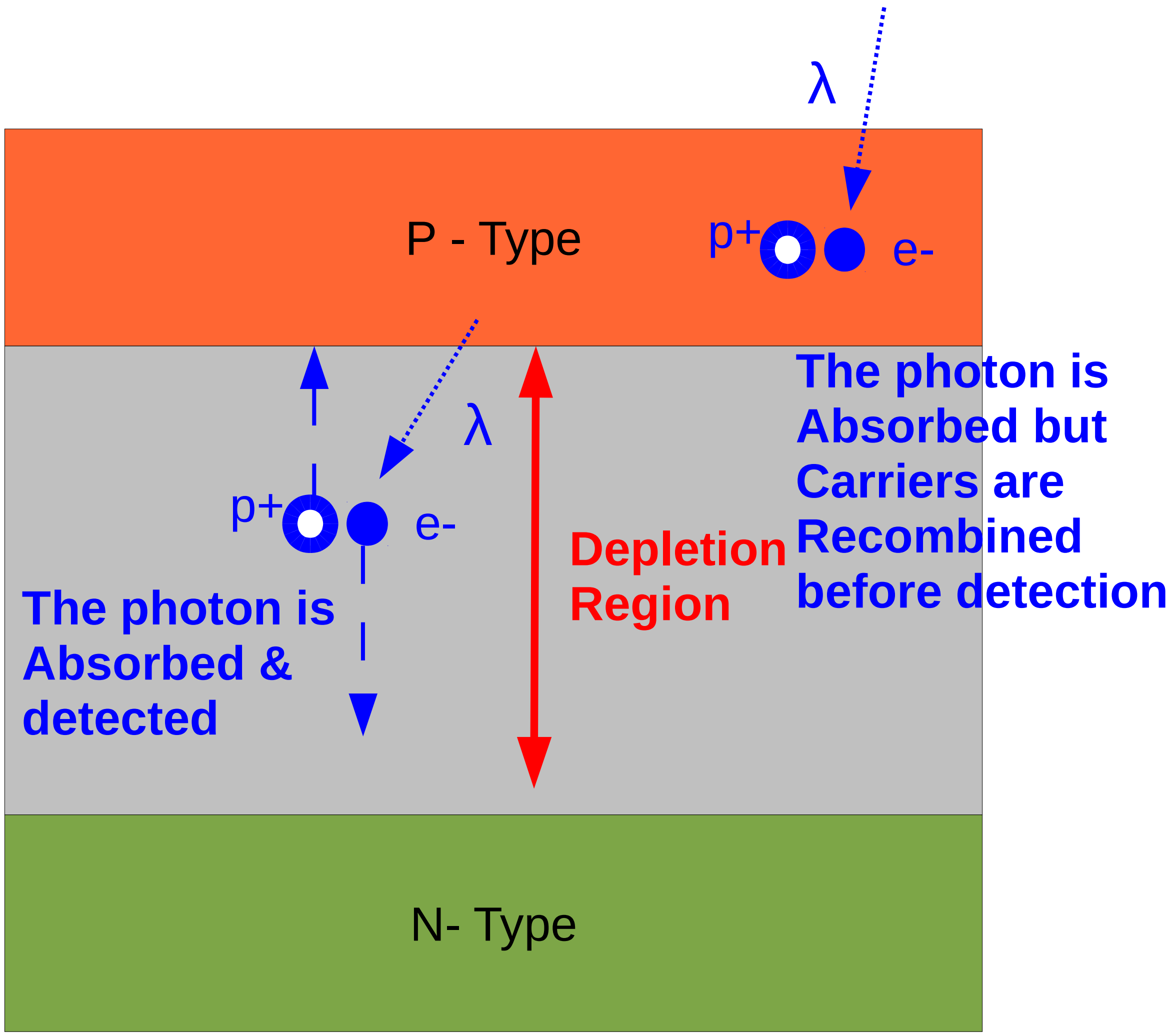


Figure L 19

Good detector design involves making the P region (facing the incoming light) as thin as possible, and making the depletion region as large as possible. For this reason, an intrinsic layer (neither P or N type) is often sandwiched in the P-N Junction. The intrinsic layer spaces out the charge trapped in the lattice, and increases the width of the depletion region. These diodes are called PIN detector diodes. The increased width of the depletion region increases the efficiency of the detector. In practice, detectors are reverse biased to increase the depletion region further and reduce capacitance.

8. Laser Chirp

Chirp was briefly mentioned earlier when we discussed extinction ratio. Like a plucked guitar string, the laser does not immediately start oscillating at the desired frequency. Since the fiber index of refraction is a function of wavelength, laser chirp can cause bit errors in systems where the fiber is long enough for the wavelength dispersion to allow these chirp wavelengths to bleed into the adjacent bit. Optical ZEROs will be accidentally detected as optical ONEs. For this reason, it would be nice to leave the laser biased at the optical ONE level, and modulate the light with a shutter external to the laser cavity.

9. The Modulator Diode

A specially designed modulator diode external to the cavity can be used as such a shutter. The modulator diode can have near zero bias making the depletion region small, and reducing the absorption of the laser light. As the reverse bias on the modulator diode is increased, the absorption is increased.

This modulator diode external to the laser cavity produces optical ONES when it has little or no reverse bias, and it produces optical ZEROS when it has reverse bias. Since the DFB laser is never being switched on and off, there is much less light produced at undesirable wavelengths. The chances of wavelength dispersion in the fiber producing a bit error are greatly reduced.

The following figure shows the laser integrated with the modulator diode:

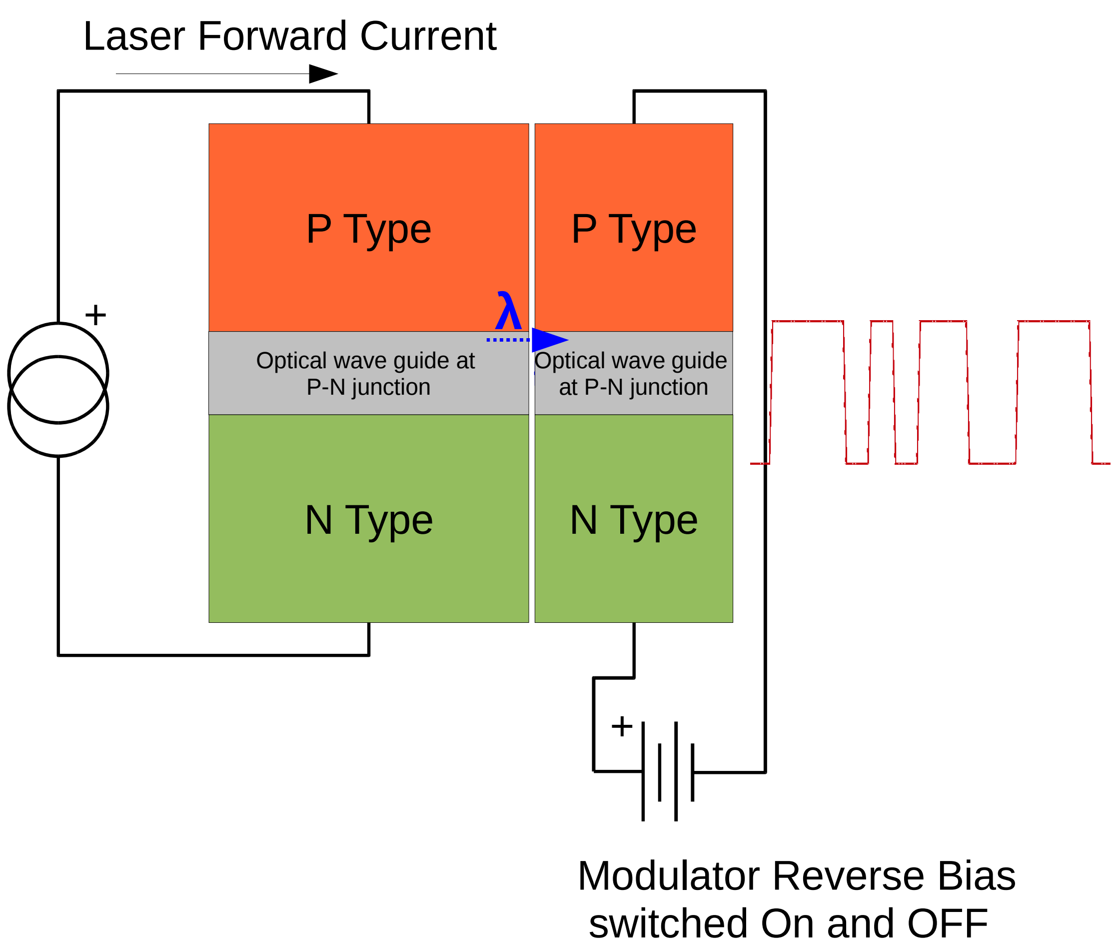


Figure L 20

The reverse bias on the modulator is switched on and off. ON causes an optical ZERO, and OFF causes an optical ONE. The exact bias points must be determined with care. Also forward bias on the modulator will cause spontaneous emission. Typically the optical ONE value is achieved with a slight reverse bias, and the optical ZERO is achieved with a strong reverse bias.

10. Mach-Zehnder modulator

Another way of achieving the desired shutter effect is to split the laser beam in two equal parts. The one part can then be delayed relative to the other by π radians. When the beam is recombined, this results in complete cancellation or an optical ZERO. When the delay is eliminated, we get constructive interference or an optical ONE. There are materials where the index of refraction is a function of electric field. In these cases, a carefully applied voltage can achieve the 0 and π radian delay. The figure below shows the Mach-Zehnder modulator.

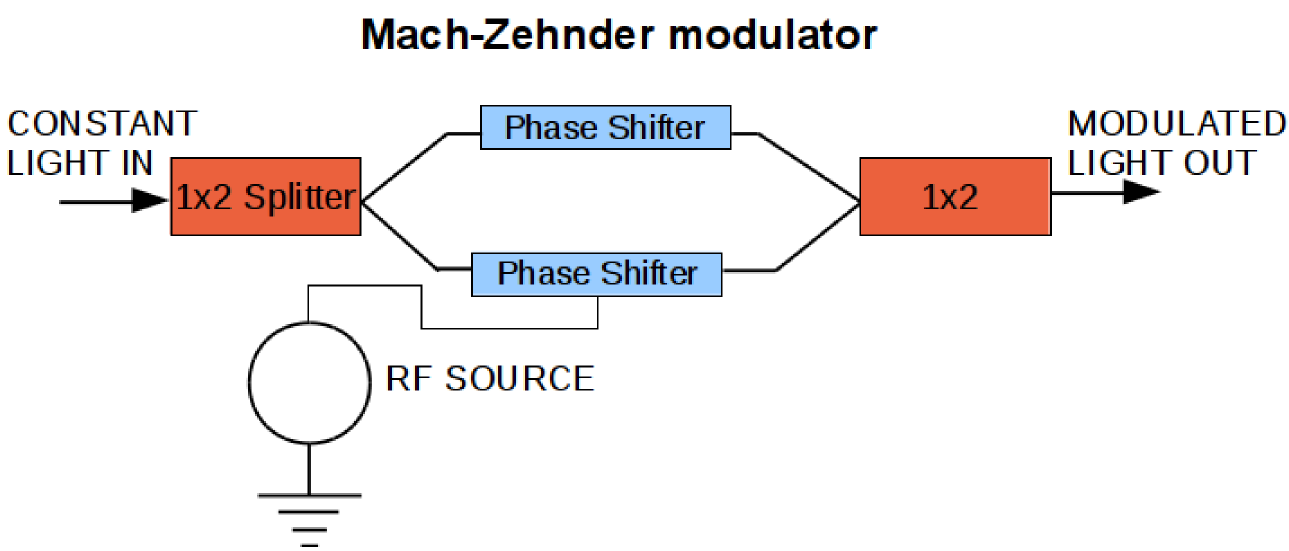


Figure L 21

These modulators are capable of high extinction ratios, and low chirp. More recent technologies allow them to be built with integrated circuit type techniques, lowering the cost. Low cost Mach-Zehnder modulators are replacing directly modulated lasers not just in longer links, but also relatively short links.

11. Laser Safety

Nothing written in this section should be viewed as superseding any warning labels on equipment or any safety warnings in the technical manuals for the equipment. This section is a discussion of laser safety principles as they apply to fiber optic systems.

In the USA the FDA (Food and Drug Administration) is charged with regulating laser safety. The CDRH (Center for Devices and Radiological Health) is a division within the Food and Drug Administration. They have placed lasers into various classes according to power and wavelength. Internationally the IEC (International Electrotechnical Commission) has produced a similar scheme in their document 60825. The older Food and Drug Administration system used Roman numerals for the laser classes. The Food and Drug Administration and International Electrotechnical Commission have harmonized their systems, and Arabic numerals are used in the new system. This is briefly summarized in the figure below:

<table>
<tr><th>CLASS</th><th>US: FDA/CDRH</th><th>IEC 60825
(AMENDMENT 2)</th></tr>
<tr><td>Class 1</td><td colspan="2">• No known hazards during to eye or skin during normal operation
• Note: Service Operation may require access to hazardous embedded lasers</td></tr>
<tr><td>Class 1M</td><td>N/A</td><td>• No known hazards to eye or skin, unless collecting optics are used</td></tr>
<tr><td>Class 2a</td><td>• Visible lasers not intended for viewing.
• No known hazards up to maximum exposure time of 1000 seconds</td><td>N/A</td></tr>
<tr><td>Class 2</td><td colspan="2">• Visible lasers
• No known hazard with 0.25 seconds (aversion response)</td></tr>
<tr><td>Class 2M</td><td>N/A</td><td>• No known hazard with 0.25 seconds (aversion response) unless collecting optics are used</td></tr>
<tr><td>Class 3a</td><td>• Similar to Class 2 with the exception that collecting optics cannot be used to directly view the beam
• Visible only</td><td>N/A</td></tr>
<tr><td>Class 3R</td><td>N/A</td><td>• Replaces Class 3a (with different limits)
• 5 x Class 2 limit for visible
• 5 x Class 1 limit for some invisible</td></tr>
<tr><td>Class 3B</td><td colspan="2">• Medium-powered (visible or invisible)
• Intrabeam and specular eye hazard
• Generally not a diffuse or scatter hazard
• Generally not a skin hazard</td></tr>
<tr><td>Class 4</td><td colspan="2">• High powered lasers (visible or invisible)
• Acute eye and skin hazard intrabeam, specular and scatter conditions
• Non-beam hazard (fire, toxic fumes, etc.)</td></tr>
</table>

Source: http://www.erchonia.com/references/laser-classifications

Figure L 22.

In fiber communication systems the light is infrared and far below the power of lasers used to weld or cut metal. Therefore, the chief concern is damage to the eye. The designers usually assure that all the power is contained in the chassis and the fiber, making the systems class 1 for the end users. Installers and users of these systems are not likely to be exposed to harmful laser radiation. The usual signal wavelengths used are 850 nm, 1300 nm and 1550 nm. Now 600 nm is near the edge of your ability to see red. Laser pointers are about 630 nm. Somewhere above 1100 nm the light will not focus well on your retina. If you can see the light, your body will automatically protect itself. You will flinch, squint, blink, etc. The region of light between 600 nm and 1100 nm is of most concern. The energy can reach your retina, and **your flinch response will not protect you**. Your first knowledge of damage will be loss of vision due to retina damage. This has given rise to the cynic's first rule of laser safety, “Do not look into the laser with your remaining good eye.” Thankfully, most systems are 1300 and 1500 nm and the 850 nm systems are usually low power. The other thing that tends to protect the user is that the light out of the fiber diverges quickly. You can think of the light coming out of the fiber in about a 30° cone. So even if there is power in the fiber, the energy density will rapidly disperse with distance. This dispersion is enough to protect the worker, unless the power is very high or it is refocused. **Never look at the end of the fiber with any optics** (i.e. eye loupe, microscope, etc.) If you have to inspect the end of a fiber for damage, assure that the laser(s) are **OFF**. Many inspection scopes in the field use small video screens, or a filter such as KG3 glass, to preclude possibility of injury. Made by Schott, KG3 attenuates infrared while allowing visible light through. Perhaps the most dangerous laser in fiber systems is the pump laser for fiber amplifiers. They create a population inversion in erbium doped fiber. The population inversion without feedback causes the fiber to amplify 1550 nm light. These pump lasers are high power, and are usually around 980 nm. Remember, between 600 nm and 1100 nm is the most dangerous to the retina. Thankfully, the designers of the amplifiers assure all the 980 nm light is contained in the fiber amplifier. I have personally measured several of these while doing a survey for laser safety, and the 980 nm light was negligible outside the fiber amplifier. It should be noted that the 1550 nm light in systems with amplifiers can achieve very high powers +30 dBm (1000 mW) is common. Any dirt on the fiber connectors in these systems can be vaporized and immediately damage the fiber ends. Remember, the single mode fiber ends are only 9 µm. Another opportunity for injury comes from red fiber inspection lasers. These are often fairly high power approxiately 1 to 5 mW (class 2 or 3R). They are usually HeNe (Helium Neon) with a wavelength of 633 nm. The red light is launched into the fiber, and any crack or bad fusion splice, etc. will scatter the red light, making the location of the fault obvious. The rule of never using magnification to look at the fiber end is especially important when using these red fiber diagnostic lasers. A fiber inspection scope with a video screen is the best choice since a filter such as KG3 will not protect well at 633 nm. However, these systems are safe. If you never defeat an interlock, and if you never look at an active fiber end especially with optics, you can safely work with these systems.